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Interferometric adaptive optics for high-power laser beam correction in fast ignition experiments

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Abstract. We present the design for a high-speed adaptive optics system that will be used to achieve the necessary laser pointing and beam-quality performance for initial fast-ignition coupling experiments. This design makes use of a 32x32 pixellated MEMS device as the adaptive optic and a two-channel interferometer as the wave-front sensor. We present results from a system testbed that demonstrates improvement of the Strehl ratio from 0.09 to 0.61 and stabilization of beam pointing from $\sim 75\mu\text{rad}$ to $<2\mu\text{rad}$.

1. Introduction

With the recent completion of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, an experimental facility now exists which is capable of conducting the first full-scale fast-ignition (FI) experiments. As the first step toward this goal, a near-term experimental campaign is being planned to quantify the total fast-ignition drive-energy requirements.

This experiment will make use of the Advanced Radiographic Capability (ARC) diagnostic system which is currently under construction at the NIF. This system uses one quad of the NIF amplifier chain to generate high-peak-power pulses, with pulse widths ranging from 1 to 50 picoseconds, and total quad energies ranging from ~ 6 to ~ 20 kJ, limited by the damage threshold of the final optics. As shown in Fig. 1(a), each beam in the quad is split vertically in two to produce four split-pairs. The gap in each beam allows for the use of eight independently-timed laser beams for the ARC diagnostic. Each half of the beam uses separate compressor optics.

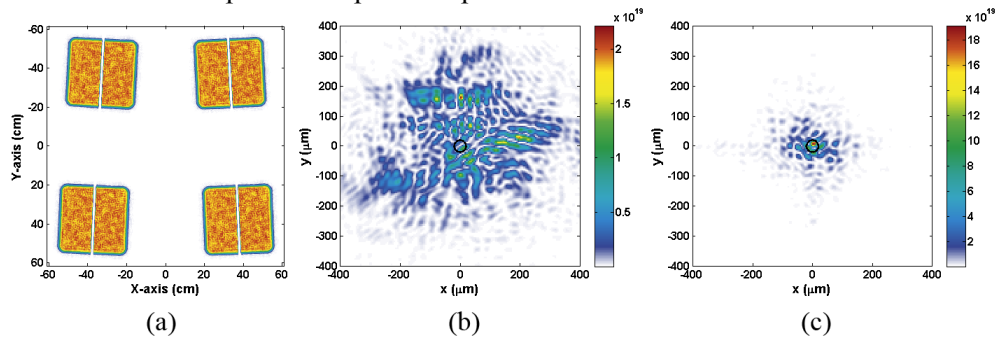


Figure 1. (a) Near-field intensity of ARC quad, (b) simulated instance of the far-field intensity for an uncorrected ARC quad, and (c) simulated far-field intensity of the ARC beam with proposed correction. The black circle in (b) and (c) indicates the 40- μm cone tip.

The goal of the first sub-ignition-scale experiments is to measure the laser-to-electron energy coupling. Currently this conversion efficiency has a large uncertainty, with the value expected to be anywhere from 10-40% [1]. In order to plan for the full-scale FI experiments, this parameter must be known to greater precision. Hydrodynamic and particle-in-cell simulations have indicated that for these initial FI coupling experiments, the ARC quad of beams will need to deliver 3-4 kJ of total energy to within a 40-50 μ m diameter spot at the end of a FI cone target. The laser parameters for the current ARC configuration and those necessary to achieve the coupling experiment goals are listed in Table 1.

Requirement	Expected ARC Performance	Campaign I FI Electron Coupling Demo
Energy in 40-50 μ m diameter	< 300J	3-4 kJ
Intensity (W/cm ²)	$\sim 1.0\text{E}+18$	$1.0\text{E}+20$
Pointing Stability	$\pm 75 \mu\text{m}$	$\pm 10 \mu\text{m}$
Pulse Length	1-50 ps	5 ps

Table 1. Laser requirements for the fast ignition campaign.

High-speed measurements taken on one of the NIF beamlines indicated that the RMS spot-displacement from target chamber center (TCC) was <17 μ m over a 12-second period, and that peaks in the vibration spectrum occurred between 20 and 60 Hz [2]. Because of the additional optics needed in the ARC beamline for compression, the pointing RMS is expected to be $\geq 75\mu\text{m}$, and the Strehl ratio of a single beam of the quad is expected to be anywhere from 0.09 to 0.36. To achieve the laser requirements for the fast ignition experiments a system must be in place to improve laser pointing and beam quality. We have proposed using an interferometric adaptive optics system to achieve the laser pointing and beam-quality requirements on the ARC beamline [3].

2. Adaptive Optics System Design

Because the capability to do fast-ignition experiments was not included as part of the original design for NIF and ARC, the architecture of these existing systems limited the design space for the adaptive optics (AO) upgrade. We chose to use an interferometric adaptive optics system based on a previously demonstrated system at LLNL[4] because it can be incorporated into the existing system architecture. The interferometric adaptive optics system consists of a wavefront sensor (WFS) camera, a MEMS device which consists of a 32x32 array of piston-only, 300- μ m-pitch actuators, and a single-longitudinal-mode laser which serves as both the reference in the interferometer arm and the point source at target chamber center. The system operates as follows:

1. Just before the shot, a $\sim 10\text{nJ}$, nanosecond, narrow-linewidth laser propagates from an angle-cleaved fiber optic placed across the fast-ignition cone opening.
2. The laser back-propagates through all eight of the ARC split-beam beamlines to four separate phase conjugation engines (PCE's) at Relay Plane 10 (RP10) on NIF.
3. At the PCE, shot-noise-limited coherent-detection is used by interfering the returning laser pulse with a local oscillator, which is the same illumination laser used in step 1. The shot-noise limit is important because of the high-losses in the NIF amplifier chain ($\sim 60\text{dB}$) that are necessary for reducing laser backscatter.
4. The two-channel interferogram (a sine and cosine channel is measured) is processed to yield the wavefront (tip/tilt and higher-order wavefront distortion) characterizing the beam path.
5. The wavefront correction & electronic offset (e.g. pointing shift) is applied to the MEMS device and tip-tilt mirror.
6. The fast ignition laser pulse samples the MEMS and is pre-corrected for RP10-to-Target aberrations.

Because we plan to use a pixellated MEMS device, phase-unwrapping will not be necessary, which minimizes the calculation requirements and allows for higher-speed operation. Furthermore, because the point source will be attached to the target, any small motions in the target will be accurately tracked by the system. This is important for hitting the target to within $10\mu\text{m}$ (given the focal length of the ARC beamline, this translates to a $\sim 1\mu\text{rad}$ pointing requirement).

A scaled testbed has been assembled to test the performance of the proposed adaptive optics system before implementation on the ARC beamline. The goal of the testbed is to measure the system performance as characterized by a handful of parameters: pointing accuracy, pointing correction bandwidth, residual-wavefront-error as a function turbulence-strength and spatial- and temporal-frequencies, and the ability to phase the two halves of a split beam.

The degree to which the wavefront must be corrected has been determined by simulation. Monte Carlo simulations suggest that with a pointing error of $10\mu\text{m}$ and $\lambda/10$ phasing between shared beam apertures, the single-beam residual wave-front error must be $< \lambda/10$ in order to have a significant probability of achieving $> 3\text{kJ}$ in a $50\text{-}\mu\text{m}$ bucket. This corresponds to a single-beam Strehl ratio $S \approx 0.65$. These results are shown in Fig. 2.

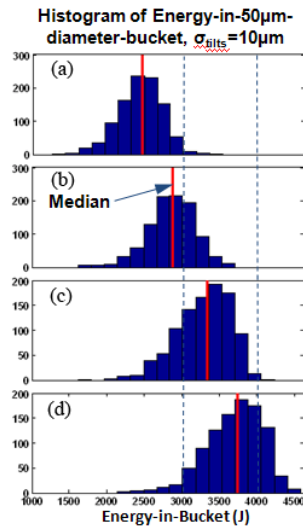


Figure 2. Histogram of energy in a $50\mu\text{m}$ bucket with a pointing uncertainty of $\pm 10\mu\text{m}$ for a residual phase of (a) $\sim \lambda/7$, (b) $\sim \lambda/8$, (c) $\sim \lambda/10$, and (d) $\sim \lambda/12$. The 3-kJ and 4-kJ points are indicated by the dotted line, and the median value of the distribution is indicated with the solid red line.

3. Testbed Results

Because significant improvements to the ARC performance can be made by pointing-only improvements (no wavefront correction), we first tested the ability of the adaptive optics system to correct for pointing-only errors. We did this by using two fast-steering mirrors, each placed in a relay plane of the final focusing objective, one to induce a randomly-generated pointing jitter on the beam, and the second to correct for this disturbance. Because the wavefront sensing system is sensitive to waves of tilt across the aperture and not absolute pointing angle in the far-field, achieving pointing stability to less than $9.3\mu\text{rad}$ in the lab corresponds to pointing stability of less than $1\mu\text{rad}$ on NIF. Similarly, $75\mu\text{m}$ of tilt at NIF target chamber center corresponds to an angle-error of $\sigma_{\text{tilts}} = 8.4\mu\text{rad}$ on the ARC beamline which corresponds to $\sigma_{\text{tilts}} \sim 78\mu\text{rad}$ in the lab. The timing of the lab has also been scaled. It is expected that dedicated hardware will be required to run the system on NIF at $\sim 1000\text{ Hz}$, but for flexibility the lab demonstration is operated through software which limits the repetition rate of the system to $\sim 100\text{ Hz}$.

We compared system performance for five different tilt-calculation algorithms: one used the Goldstein algorithm [5] to unwrap the phase and extracts the tilts by a least-squares fit of a plane to the phase, one uses a simple technique of averaging the tilts between neighbouring pixels in the phase calculation, and the remaining three determine the far-field focal spot position by taking the FFT of the measured phase for three different resolutions. The results for one particular test are shown in Fig. 3. In this test the measurements were taken and the corrections were applied at 100 Hz , and the

bandwidth of the applied jitter was 0.2Hz (a) and 2.0Hz (c). Three of the five algorithms achieved the fast ignition requirement that $\sigma_{\text{tilts}} < 9.3 \mu\text{rad}$. It is not yet known what the jitter spectrum will be on the ARC beamline, but these results indicate that a 1-kHz system on the ARC beamline could sufficiently correct for a 10-Hz vibration with a 8.4- μrad amplitude.

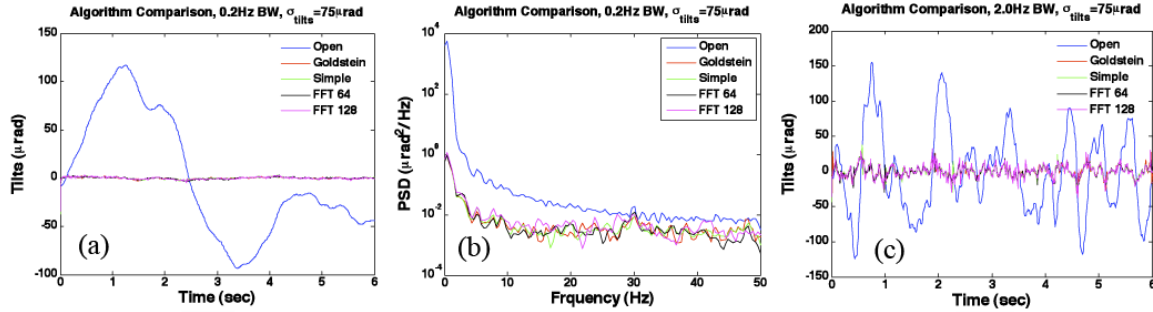


Figure 3. (a) Residual tilts for 5 algorithms and 0.2Hz bandwidth, 75 μrad disturbance, compared to open loop, (b) PSD of measured tilts, and (c) residual tilts for 2.0Hz bandwidth disturbance.

Preliminary tests have also been performed using the 32x32 MEMS device to correct for a static phase disturbance. In these tests a static phase plate was placed in the beam, the two-channel interferogram was measured, and the wrapped phase correction was applied to the beam. Figure 5(a) shows the strength of the phase disturbance, and the RMS of the phase is $\sigma_{\text{phase}} = 4.1$ radians. Figure 5(b) shows the far-field spot when no phase correction is applied to the MEMS device, and the resulting Strehl ratio is 0.09. Figure 5(c) shows the far-field spot with the MEMS correction applied and results in a Strehl ratio of 0.61. Even though this level of phase disturbance is greater than we expect to encounter on the ARC beamline, we still achieve a Strehl ratio in line with what is required to meet the fast ignition requirements. We are currently transitioning to a high-speed correction system and will at that point measure the dynamic properties of the phase correction system.

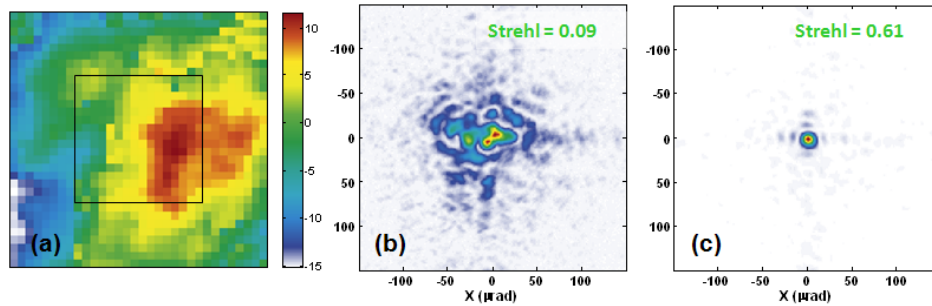


Figure 4. (a) Measured and unwrapped phase disturbance. The black box indicates the area of the MEMS that was used for this measurement, which has been restricted due to manufacturing turned-down-edge of the substrate. (b) Far-field of the uncorrected beam, (c) far-field of corrected beam.

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